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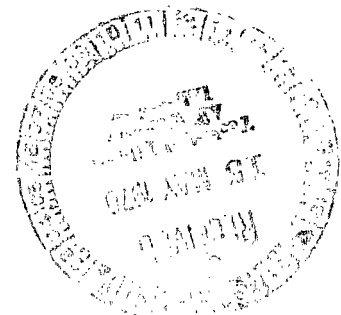
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COMMENTS ON SEVERAL REDUCED-GRAVITY SIMULATORS USED FOR STUDYING LUNAR SELF-LOCOMOTIVE TASKS

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16. Abstract <p>The uncertainties concerning the physical capabilities and limitations of an explorer in performing locomotive and other working tasks in the lunar environment have led both industrial and governmental organizations to develop a variety of reduced-gravity simulators. This report presents a subjective review of the "feel" and operating characteristics of some of the simulators which are currently being used. The observations are those of an engineer who has acted as a test subject in a number of the currently developed simulators.</p>		13. Type of Report and Period Covered Technical Note
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COMMENTS ON SEVERAL REDUCED-GRAVITY SIMULATORS USED FOR STUDYING LUNAR SELF-LOCOMOTIVE TASKS

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SUMMARY

The uncertainties concerning the physical capabilities and limitations of an explorer in performing locomotive and other working tasks in the lunar environment have led both industrial and governmental organizations to develop a variety of reduced-gravity simulators. This report presents a subjective review of the "feel" and operating characteristics of some of the simulators which are currently being used. The observations are those of an engineer who has acted as a test subject in a number of the currently developed simulators.

In general, the underwater, airplane, and inclined-plane techniques have approximately the same feel for comparable conditions. The inclined-plane technique does not have either the time limitation of the aircraft or the velocity limitations of the underwater approach, but it is limited to only three degrees of freedom. The vertical simulation approach has a different feel due to the suspension techniques and offers six degrees of freedom which are limited by the system restraints. It has no time or velocity limitation if treadmills are employed.

Studies of lunar self-locomotive tasks should be meaningful if (1) simulators matched to the particular task are selected, (2) at least two appropriate simulation techniques are employed, (3) test subjects with broad experience are used, and (4) the effects of the simulator restraints on the data are evaluated.

INTRODUCTION

The uncertainties concerning the physical capabilities and limitations of an explorer in performing locomotive and other working tasks in the lunar environment have led both industrial and governmental organizations to develop a variety of reduced-gravity simulators to permit studies under controlled laboratory conditions. The fact is generally recognized, however, that any simulation is limited and that the degree of fidelity to the real-life situation can vary significantly depending on the techniques utilized and the adequacy of the system. To date only a few studies have been directed toward comparing the performance and characteristics of the varied and widely dispersed reduced-gravity

simulators. (See refs. 1 and 2 for examples.) Correlation of results obtained by using different simulators is often difficult and perhaps meaningless at the present time. The purpose of this report is to summarize the observations of an engineer who has acted as a test subject in a number of the currently developed simulators. Of particular interest are some of the similarities and differences in the feel and operating characteristics that were encountered at simulated lunar-gravity conditions. In no way are these observations intended to represent a quantitative evaluation of the overall performance or fidelity of the techniques and facilities discussed in this report.

SIMULATION TECHNIQUES AND EQUIPMENT

Table I presents the physical characteristics of the various simulators in which the author has acted as a test subject. The simulators are of four basic types: inclined plane (refs. 2 to 7), vertical suspension (refs. 7 to 11), underwater (ref. 12), and airplane (modified Keplerian trajectory). A discussion of the general features of each type of simulator is given herein.

Inclined-Plane Simulators

The inclined-plane simulators (table I, items 1 to 5) provide simulated lunar gravity by supporting a subject on his side in an inclined attitude of approximately 9.5° from the horizontal. A resulting force equal to one-sixth of the subject's weight is supported by his feet (ref. 2). The body members are suspended by slings and cables (fig. 1) attached to a lightweight overhead trolley unit (fig. 2). The trolley is free to move along the track that is parallel to but displaced from directly over the walkway to provide the 9.5° cable angle. The subject is thus free to walk, run, and perform self-locomotive tasks in a more or less normal manner, even though he is constrained to move essentially in one plane.

All the inclined-plane simulators discussed in this report have been patterned after the reduced-gravity walking simulator designed and patented by the NASA Langley Research Center (refs. 2 to 5); they differ primarily in the length of the cable support system and the type of walkway used. Support-cable lengths on the inclined-plane simulators that were evaluated ranged from 17 to 150 ft (5.2 to 46 m). The system with a 17-ft (5.2-m) cable length is illustrated in figure 3, and the 150-ft (46-m) system is shown in figure 2. Two types of fixed walkways were utilized: the straight walkway as used in the original Langley simulator (ref. 2 and fig. 2) and a circular walkway as shown in figure 4. Straight walkways varied in length up to a maximum of 200 ft (61 m) and were either fixed surfaces or motorized treadmills. Treadmills varied in length from 4 to 16 ft (1.2 to 4.9 m) and in width from 1.5 to 4 ft (0.45 to 1.2 m) and had maximum operating speeds up to 15 ft/sec (4.55 m/sec).

The circular walkway used with item 4 of table I (ref. 6) provided, in effect, a system of infinite length; however, the simulated gravity varied with the test subject's speed because of the centrifugal force acting on the subject as he proceeded around the walkway. The circular-walkway simulator was 94 ft (28.6 m) in diameter and was designed so that lunar gravity was simulated when the subject was moving at 4 mph (6.4 km/hr).

Vertical-Suspension Simulators

Lunar-gravity simulators with vertical-suspension systems (table I, items 6 to 11) were designed to support five-sixths of the subject's weight when he is in an erect position. All the vertical-suspension simulators consisted of a gimbaled body-support system, a vertical takeup system, and an overhead system which provided two degrees of translational freedom. The body-support system was designed so that the pivot points could be aligned with the center-of-gravity location of the subject.

Vertical takeup systems.- Three methods of generating the constant force required to partially support the test loads were used: negator springs (refs. 8 to 11), counterbalances (ref. 7), and pneumatic systems.

Ideally, a negator-spring system like that illustrated in figure 5 is matched to a specific subject's weight and the spring must be changed to accommodate a different weight. However, the usual practice is to size the springs for the heaviest weight to be used and then bring the system weight to the design conditions by using ballast weights. The additional weight is usually placed at some position on the gimbal.

For the counterbalance system a balancing weight equal to five-sixths of the subject's weight was attached to the support system by means of cables and pulleys (fig. 6). The static difference between the counterbalance and weight of the subject produced a force equal to one-sixth of the subject's weight at his feet. Because the static unbalance accelerates the total mass of the system, as an Atwood machine, the subject's free-fall acceleration will be $\frac{1}{11}$ g.

Two types of pneumatic systems were tried: the first employed a stalled turbine; the second, a long, slender pneumatic cylinder. The stalled-turbine system (fig. 7) uses a small airplane starter turbine which produces a nearly constant force under the low-speed conditions at which it operates. The turbine is supplied with pressurized air by means of a standard airplane auxiliary power unit normally used with a turbine starter. The force level of this system is readily adjustable by varying the supply air pressure from the power unit. The unique, low-inertia pneumatic cylinder (fig. 8), which was developed at the NASA Manned Spacecraft Center (MSC), was designed to support loads up to several hundred pounds (approximately 2 kN) by means of air pressure. The weight of the load supported was controlled to within a few ounces (about 1 N) of the desired value

by a pneumatic servomechanism. Hysteresis in the system was a few ounces for a 400- or 500-lb (1.8- or 2.2-kN) load.

Overhead translation systems.- Three basic methods were used for supporting and maintaining the suspension system vertically over the subject as he moved about the test surface: a traveling bridge (fig. 9), an air-bearing-supported boom and dolly (fig. 7), and a magnetic air-bearing system (refs. 8 to 10 and fig. 5). (See table I.) All the overhead systems were unpowered; that is, the subject pulled the system along as he moved. The large crane, however, had a powered bridge unit that was servo controlled to remain over the subject and an unpowered dolly located beneath the bridge. One end of the air-bearing-supported boom was pivoted and the other end was free to swing on air pads. Air pads were also used to support the dolly, which was free to move along the boom. The magnetic air-bearing system was suspended from a steel ceiling. Safety lines were attached to each magnetic air-bearing unit in order to prevent injury to the subject should a magnetic bearing inadvertently separate from the ceiling. In most cases efforts had been made to keep the mass and friction of the overhead system to a minimum so that the motion of the subject would not be restricted.

Gimbaled body-support systems.- All the vertical suspension systems used basically the same type of gimbal assembly for attaching the vertical support cable to the torso-harness system to provide the rotational freedom of the subject. (See figs. 5, 10, and 11.) The yaw axis coincided with the cable; the roll axis, with the junction of the C-brace and yoke; and the pitch axis, with the junction of the yoke and body-harness system. Each system has a method of adjusting the position of the body restraint with respect to the gimbal to insure proper placement of the subject's nominal center of gravity.

Body-support systems.- Four basic types of body-harness or support systems were used. Two, which were designed for use by a subject in a full pressure suit, employed the suit as part of the support system, and two were designed for use by a subject in shirt sleeves.

Of the systems used with a pressure suit, the first employed a waistband (ref. 11 and fig. 10) which was placed around the subject in an unpressurized suit. When the suit was pressurized, the subject was supported primarily at the soles of his feet by the boots of the suit, provided that the leg length of the suit was properly adjusted to prevent undesirable pressure in the crotch area. The second system employed a fiber-glass full-body vest (fig. 11). The vest was constructed in two parts (front and back halves), which were secured in place on the suited subject with the back half attached to the gimbal system. Pressurizing the suit caused it to expand to fit the vest and again allowed the suit to be the main body support. This vest system could also be used with a subject in shirt sleeves although he would not be as comfortable as in the pressure suit because of the lack of support at his feet.

Additional body-support systems, designed for shirt-sleeve operations, were investigated. Although the net suit (fig. 6) proved to be fairly comfortable and offered minimum restraint to movements, the net-suit support system, because of its gimbal arrangement, restricted the subject to a forward body lean of an estimated 20° or less. Another shirt-sleeve system considered (fig. 5) was still in the prototype stage. It used a bicycle seat to distribute most of the supported load over the area of the lower buttocks (the ischial tuberosities of the pelvis). The arms and legs were each supported separately by small vertical takeup units (fig. 5 and refs. 8 to 10).

Underwater Simulation

Underwater simulation has recently received much attention because of its successful use in the Gemini program (ref. 12). However, only limited effort has been devoted to applying the water-buoyancy technique to lunar-gravity simulation. For the brief trials by this test subject, a standard self-contained underwater breathing apparatus (scuba) and a wet suit were worn in an indoor swimming pool 9 ft (2.7 m) deep at its deepest point. Neutral buoyancy was first obtained by attaching lead weights to the wet suit so that, while holding his breath, the subject would stay in a fixed position regardless of attitude. Lead equal to one-sixth of the subject's weight was then added to obtain simulated lunar gravity. Two methods of adding weights were evaluated: First, all the weights were placed around the subject's waist; and second, the weights were distributed on the legs, trunk, and arms in proportion to the normal weight of each part of the body.

Airplane Simulation

The C-131B airplane produced a simulated lunar-gravity environment by flying a modified Keplerian trajectory. (See ref. 2.)

TEST SUBJECT'S BACKGROUND

The engineer who acted as the test subject has approximately 7 years of simulated lunar- and zero-gravity experience dealing with the dynamic capabilities of both vehicles and humans. He was a partner in the development of the inclined-plane technique (ref. 2), acted as a test subject for the work reported in references 2 to 5, and participated in the development of the rotating space-station simulator (ref. 13). He is qualified for underwater testing which requires scuba equipment and for pressure-suit work. The subject has accrued a number of hours in various pressure suits, including the Mark IV, Gemini G2C, AXIL, A4H, and A6L.

OBSERVATIONS AND DISCUSSION

The following discussion is a summary of the comments of the test subject after a tour in which he had a workout in several of the simulators discussed previously. The comments concern both those simulators that he had worked with on the tour and those that he had previously used.

Treadmills

Prior to discussing each type of simulator, a discussion of the types of walkways used is in order. The inclined-plane simulator with a straight walkway and the vertical simulator both require that a treadmill be used if steady-state metabolic cost for various walking and running velocities is to be obtained. The larger treadmill units appear to be superior to the smaller units in many ways. The smaller units virtually eliminate the ability to obtain any visual motion cues from the moving belt; therefore, any slight misstep tends to cause the subject to either overrun or be forced off the back of the treadmill. Consequently, in some cases handrails have been provided to insure that the subject remains on the treadmill. Handrails are objectionable for studies of locomotive gaits and energy expenditures because they decrease the need for fine balance control associated with unassisted walking and running. The larger treadmills allow ample room for the subject to use part of the treadmill belt as a visual speed reference and ample distance for the subject to regain his balance after a misstep without being forced off the treadmill.

Running on the treadmill involved one problem that the subject did not encounter when running on the fixed straight walkway: each time his foot made contact with the treadmill he received a significant impact. This effect was particularly noticeable when the subject was running in a pressure suit. The impact shock could be minimized by adjusting the leg motions so that the relative velocity between the subject's feet and the treadmill at contact was approximately zero.

Inclined-Plane Simulators

For the system with the 17-ft (5.2-m) cable length, the change in simulated gravity with a change in the subject's height was noticeable when he attempted to squat or jump. A plot of simulated gravity level as a function of the subject's center-of-gravity height from the walkway is given in figure 12. Furthermore, when the subject attempted to start walking, the short cable length and the small amount of friction in the dolly combined to cause a sensation of pivoting at some point above the floor (in the knee area) rather than at the normal point, his feet. This sensation was present only for the initial step and was not noticeable during walking. For the system with a 150-ft (46-m) cable length, very little effect of gravity gradient was noted for maximum jumps or for climbing a ladder to a height of approximately 10 ft (3 m).

Few differences between the circular walkway and the flat walkway were observed for the various locomotive gaits employed. The subject experienced no significant difficulty as he walked, loped, and ran on the circular walkway, dressed first in shirt sleeves and then in a pressure suit pressurized to a differential of 3.7 psi (25.5 kN/m²). The noticeable curvature of the walkway did not produce any disturbing visual effects and did not interfere with the subject's ability to observe and negotiate over a large number of various sized objects mounted on the surface to simulate lunar rocks. The small change of gravity level with change in centrifugal force as speed was varied was imperceptible.

Vertical-Suspension Simulators

There were a number of differences in the vertical-suspension simulators which had some influence on the simulation.

Vertical takeup systems.- The negator-spring system has the advantage of being relatively simple; however, the vertical travel available when stock negator springs were used was a noticeable limiting factor. One system had only 9 inches (22.9 cm) available for vertical travel; consequently, the subject was consistently making contact with the upper or lower stop. For any rapid vertical motions, the response of the system was slow, apparently because of the hysteresis of the springs.

The response of the counterbalance system, as mentioned previously, is limited to something less than $\frac{1}{6}g$ downward acceleration. This reduced acceleration was the apparent cause of the floating sensation experienced by the subject when he attempted to walk or run. Because the feel of the counterbalance system differs substantially from that experienced in any of the other simulators, it was concluded that the locomotive results obtained by using this simulator would be unrealistic. Metabolic measurements obtained with the counterbalance system (ref. 7) tend to confirm this opinion, as the energy cost of walking at speeds greater than 1.2 mph (2 km/hr) did not increase significantly with increased speed, in contrast with what would be expected.

The stalled-turbine system appeared to provide constant support in the static situation; however, the dynamic response of the system seemed poor, apparently because of system inertia and friction.

The pneumatic-cylinder vertical takeup system developed at MSC was found to be superior to other vertical takeup systems evaluated. This system, which was used only for shirt-sleeve tests, maintained the desired load within a few ounces (about 1 N) throughout the available range of the subject's vertical motion. Vertical jumps of 12 ft (3.7 m) or more were accomplished.

Overhead translation systems.- All the bridge-dolly systems used with the vertical simulators to provide horizontal-translation freedom involved the movement of relatively

large masses, and their high associated inertia, as the subject moved. Initial attempts to walk slowly across a fixed walkway ended with the subject hopping along by pushing with both feet simultaneously, and subsequent attempts to walk normally resulted in a staggering motion. Staggering appeared to be caused by the intermittent forces which had to be developed in order to move the overhead system forward during the initial portion of each step. Once the overhead system started to move, the abrupt decrease in the retarding force on the subject caused him to pivot (yaw) about his supporting foot. This process was repeated with each step. There was no opportunity to lope or run on the fixed walkways with the bridge-dolly systems because of inadequate length.

When the treadmill was used in combination with the overhead system, the subject's initial attempts to lope or run resulted in a different type of instability problem. All the treadmills evaluated were aligned with the bridge so that fore-and-aft motions of the subject required movement of the dolly only, whereas lateral motions required movement of the much greater weight of the total overhead system, including the dolly. The forces generated by the subject's lateral motions were generally not sufficient to cause the entire system to follow these motions; consequently, a pendulous motion tended to develop. Unless the subject realized what was happening and took corrective action, the pendulous swing could diverge and cause the subject to lose his balance. Preventative action for the shirt-sleeve condition was to place the feet down in the plane of symmetry of the body directly under the bridge, to minimize the lateral motion of the body. When in the pressure suit, the subject was not able to perform this type of leg motion. However, if he leaned slightly in the direction of the contact foot at the time of pushoff, the pushoff force was out of phase with any existing pendulous swing and therefore tended to cancel the swing. This problem was noted to some degree on all the vertical simulators using a treadmill; however, once the problem was recognized, the preventative action necessary to eliminate the pendulous action was taken almost automatically by the subject.

Body-support systems.- Discussion of the body-support systems can be roughly broken into two parts, pressure-suit systems and shirt-sleeve systems.

The pressure suit, in effect, serves as the body support and allows the subject to stand in the suit with his weight supported on the soles of his feet rather than in the crotch area. Prior to the subject's first experience in a vertical simulator, the pressure suit was adjusted to fit at 1g conditions. When the subject was placed in the simulator, the suit legs lengthened so much that he stood on his toes in order to relieve the pressure in the crotch area. Standing in this position increased the difficulty of performing any self-locomotive task. In order to eliminate the problem, the pressure-suit legs were shortened approximately 1.5 in. (2.81 cm). Although this leg length made the unpressurized suit uncomfortable, once the suit was pressurized in the vertical simulator the subject could stand correctly without significant pressure in the crotch area. It is, therefore, suggested

that particular attention be given to the fit of the pressure suit in vertical reduced-gravity simulators. This is particularly important for a novice subject because he is faced with a number of other problems and may not be aware that he is standing on his toes instead of flatfooted within the suit.

Shirt-sleeve systems that provide support in the crotch area only were found to become uncomfortable quickly, whereas the systems that also individually supported the subject's legs were found to be fairly comfortable for extended periods. It is, therefore, suggested that shirt-sleeve support systems be implemented with leg supports. The net-suit support technique avoids pressure in the crotch area by distributing the load over the thighs and lower torso in a comfortable manner without undue restriction of leg movements.

Placement of the pivot points of the support system with respect to the subject's center of gravity (c.g.) is critical. The subject found he could easily distinguish the effects of pivot-point misplacement. When the pivot point was below his center of gravity, he felt topheavy; when it was above his center of gravity, he could lean at fairly large angles without falling. The latter condition made any realistic form of locomotion extremely difficult.

Underwater Simulation

In the underwater simulation, two techniques for ballasting the test subject to lunar-gravity conditions were tried, as mentioned previously. With all the additional ballast weights placed around his waist, the subject was unable to walk satisfactorily because of the buoyancy of his legs. As the subject stepped forward to initiate a walk, the center of buoyancy apparently shifted forward of the center of gravity and thereby caused the body to rotate head backward. If he attempted to lean forward to initiate the walk, his body would rotate head forward. The implication, of course, is that the center of buoyancy was below the waist. Obviously, placing all the weights at the waist is totally unsatisfactory.

Loading each of the main body segments in proportion to their weight changed the results substantially. The subject was able to walk about the bottom of the pool in a sure-footed manner with a minimum of balance problems at speeds up to an estimated 2 ft/sec (0.61 m/sec). Greater speeds resulted in excessive forward body-lean angles of 40° to 50°. The higher speed motion not only produced very significant drag forces due to the water but also caused the foot contact forces to be decreased as the planing action of the water on the body tended to provide body support.

Airplane Simulation

The time required for the subject to adjust to the airplane simulation of lunar conditions was much greater than the 20 to 30 sec of time available in any given test run;

consequently, several runs were required for the subject to become acclimatized. The space available was limited, particularly for the faster locomotive gaits; however, the six degrees of unlimited freedom available with this technique proved very useful in providing checkpoints on some of the stability problems, lateral stability in particular, that have been encountered with other simulation techniques.

COMPARISONS AND GENERAL REMARKS

A brief comparative summary of the comments on the various simulators is given in table II.

No one method of simulating reduced gravity has the capability of providing completely reliable answers to the lunar self-locomotive problems. For example, underwater simulation provides six degrees of freedom and appears to be good for studies requiring only slow movements. The inclined plane, with its three degrees of freedom, is useful for some self-locomotive studies and provides a good method for obtaining a feel for simulated lunar gravity. Vertical-suspension techniques provide six degrees of freedom which are limited by the system restraints. The mass and friction of the support systems create extraneous inputs, and the fact that the arms and legs are functioning at their earth weight must also be considered. The airplane simulation technique, while providing six degrees of freedom, is limited by the time available per trajectory; however, this technique should provide a good means of checking short-term stability if test subjects are experienced in other types of lunar-gravity simulators.

The existing types of reduced-gravity simulators should provide means of obtaining useful data on lunar self-locomotion tasks if consideration is given to the following details:

- (1) Selection of simulators should be based on the particular tasks to be performed.
- (2) At least two appropriate methods of simulating lunar gravity should be employed so that results can be cross-checked.
- (3) Test subjects should be experienced in several simulation methods.
- (4) Evaluation of the data should allow for the effects of restraints imposed by the simulators.

The simulators fall into two general categories relative to feel. The first category consists of the airplane, underwater, and inclined-plane simulators, all of which have a similar feel, apparently because the body members are subjected to their effective lunar weight. The second category consists of the vertical-suspension simulators, which have a different feel resulting from the operating characteristics of the suspension system, the dress of the subject (shirt sleeves or pressure suit), and the lack of partial support of the body extremities.

Based on the author's past experience and general observations, the way a subject walks in simulated lunar gravity indicates how well he is acclimatized. Initially, the average subject will tend to stand and walk primarily on his toes; however, with sufficient experience (15 to 20 min, depending on the subject) he generally will develop a normal heel-to-toe walk. After the subject has spent sufficient time in one simulator to develop a normal walking pattern, he can rapidly adapt to any of the other simulation techniques.

RÉSUMÉ

The comments in this report are based solely on the observations of an engineer who has acted as a test subject in a number of the currently developed reduced-gravity simulators used for studying lunar self-locomotion tasks. These comments indicate some of the similarities and differences in the feel and operating characteristics of the available simulators, but they do not represent an evaluation of the overall performance or fidelity of the reduced-gravity simulators.

In general the underwater, airplane, and inclined-plane techniques have approximately the same feel for comparable conditions. The inclined-plane technique does not have either the time limitation of the aircraft or the velocity limitations of the underwater approach, but it has only three degrees of freedom. The vertical simulation approach has a different feel and offers six degrees of freedom which are limited by the system restraints. It has no time or velocity limitation if treadmills are employed.

The existing types of reduced-gravity simulators should provide means of obtaining useful data on lunar self-locomotion tasks if consideration is given to the following details:

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Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., March 31, 1970.

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TABLE I.- REDUCED-GRAVITY SIMULATORS USED BY TEST SUBJECT FOR LUNAR-GRAVITY STUDIES

Item	Type of simulator	Body-support method	$\frac{1}{6}$ g support method	Degrees of freedom	Vertical travel		Suspension cable length		Translation method	Type of clothing worn by test subject	Ref.
					ft	m	ft	m			
1	Inclined plane	Straps	Inclined cables	3	^a 0.27	^a 0.08	17	5.18	Trolley	Shirt sleeves	7
2	Inclined plane	Straps	Inclined cables	3	^a 0.67	^a 0.20	39	11.89	Trolley	Shirt sleeves and pressure suit	2,3
3	Inclined plane	Straps or shell	Inclined cables	3	^a 2.18	^a 0.66	136	41.45	Trolley	Shirt sleeves and pressure suit	-----
4	Inclined plane	Straps	Inclined cables	3	^a 2.08	^a 0.63	130	39.62	Trolley	Shirt sleeves and pressure suit	6
5	Inclined plane	Straps	Inclined cables	3	^a 2.48	^a 0.76	155	47.24	Trolley	Shirt sleeves and pressure suit	4,5
6	Vertical suspension	Waist harness	Negator springs	6	\approx 1.0	\approx 3.05	---	-----	Dolly	Pressure suit	11
7	Vertical suspension	Net suit	Counterbalance	6	\approx 1.5	\approx 0.45	---	-----	Bridge and dolly	Shirt sleeves	7
8	Vertical suspension	Shell	Negator springs	6	1.5	0.45	---	-----	Bridge and dolly	Shirt sleeves and pressure suit	-----
9	Vertical suspension	Shell	Turbine	6	6	1.83	---	-----	Air bearings boom and dolly	Shirt sleeves and pressure suit	-----
10	Vertical suspension	Bicycle seat	Negator motors	6	6	1.83	---	-----	Magnetic air bearings	Shirt sleeves and pressure suit	8,9,10
11	Vertical suspension	Seat pan	Pneumatic	6	\approx 1.8	\approx 5.49	---	-----	Air bearings	Shirt sleeves	-----
12	Underwater	-----	Water buoyancy	6	-----	-----	---	-----	-----	Wet suit	12
13	Airplane	-----	Centrifugal force	6	Floor to ceiling		---	-----	-----	Shirt sleeves	-----

^aGravity level varies with vertical travel. Distance given is that resulting in 10-percent error. See figure 12.

TABLE II.- COMPARISON OF REDUCED-GRAVITY SIMULATORS
USED FOR LUNAR-GRAVITY STUDIES

[Experienced subject with and without suit]

Type	Comment
Inclined plane	Only three degrees of freedom
Straight walkway	Energy measurements difficult
Circular walkway, 94-ft (28.6-m) diam	Feels similar to straight walkway Provides continuous surface
Treadmill	Unusual gait, foot impact Useful for energy measurements
Vertical suspension	Six degrees of freedom Body supported by suit Extremities function at earth weight
Counterbalance	Lacks dynamic simulation
Negator spring	Overhead friction and inertia produce lateral stability problems
Stalled turbine, air pad	Overhead friction and inertia produce lateral stability problems Fair vertical response
Pneumatic vertical servo	Excellent vertical response Inertial effect on fore-aft motions
Underwater	Six degrees of freedom Slow walk only Ballasting very critical
Airplane trajectory	Six degrees of freedom Limited test time and space

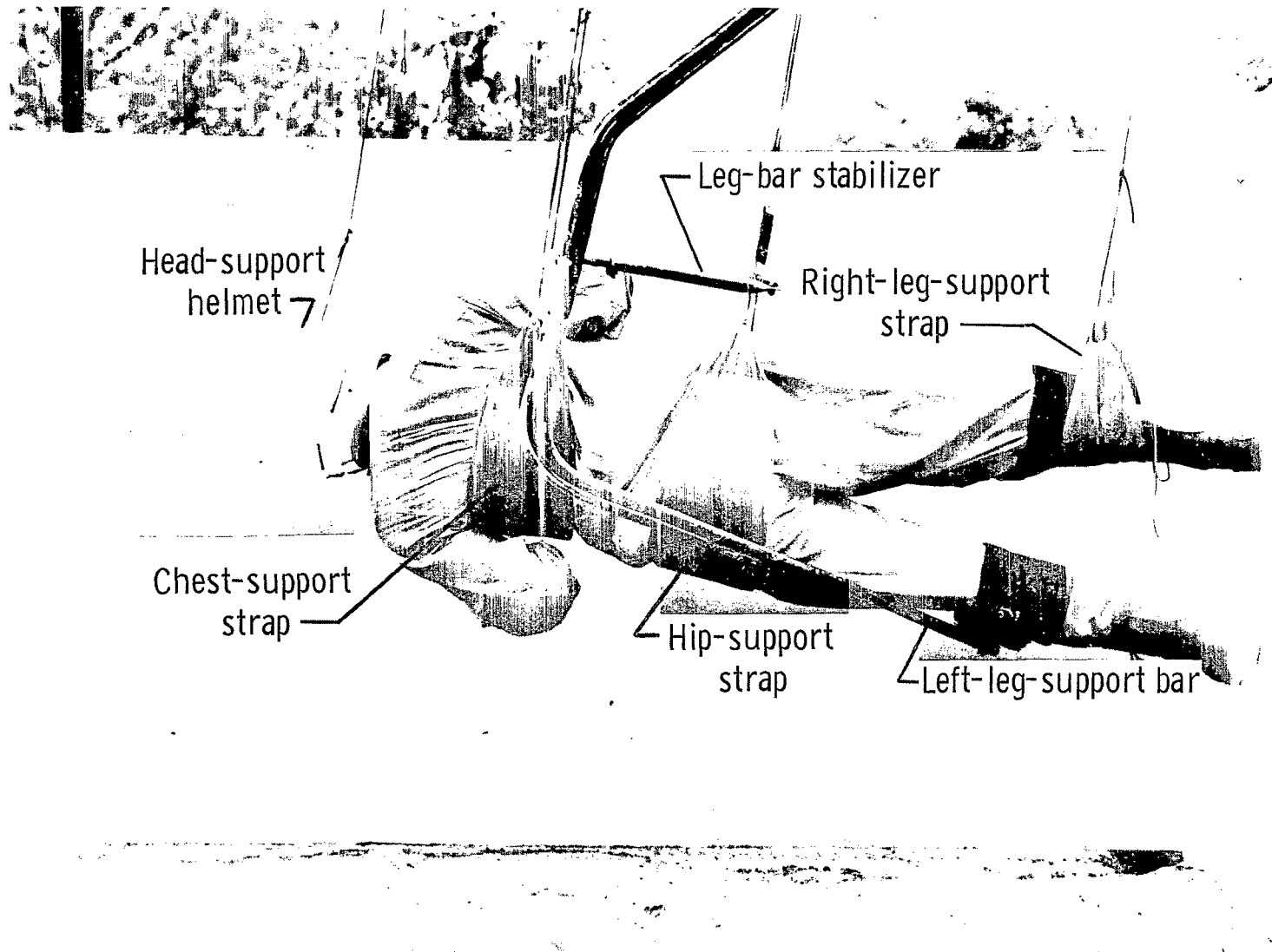


Figure 1.- Details of sling supports used with reduced-gravity walking simulator designed at the Langley Research Center.

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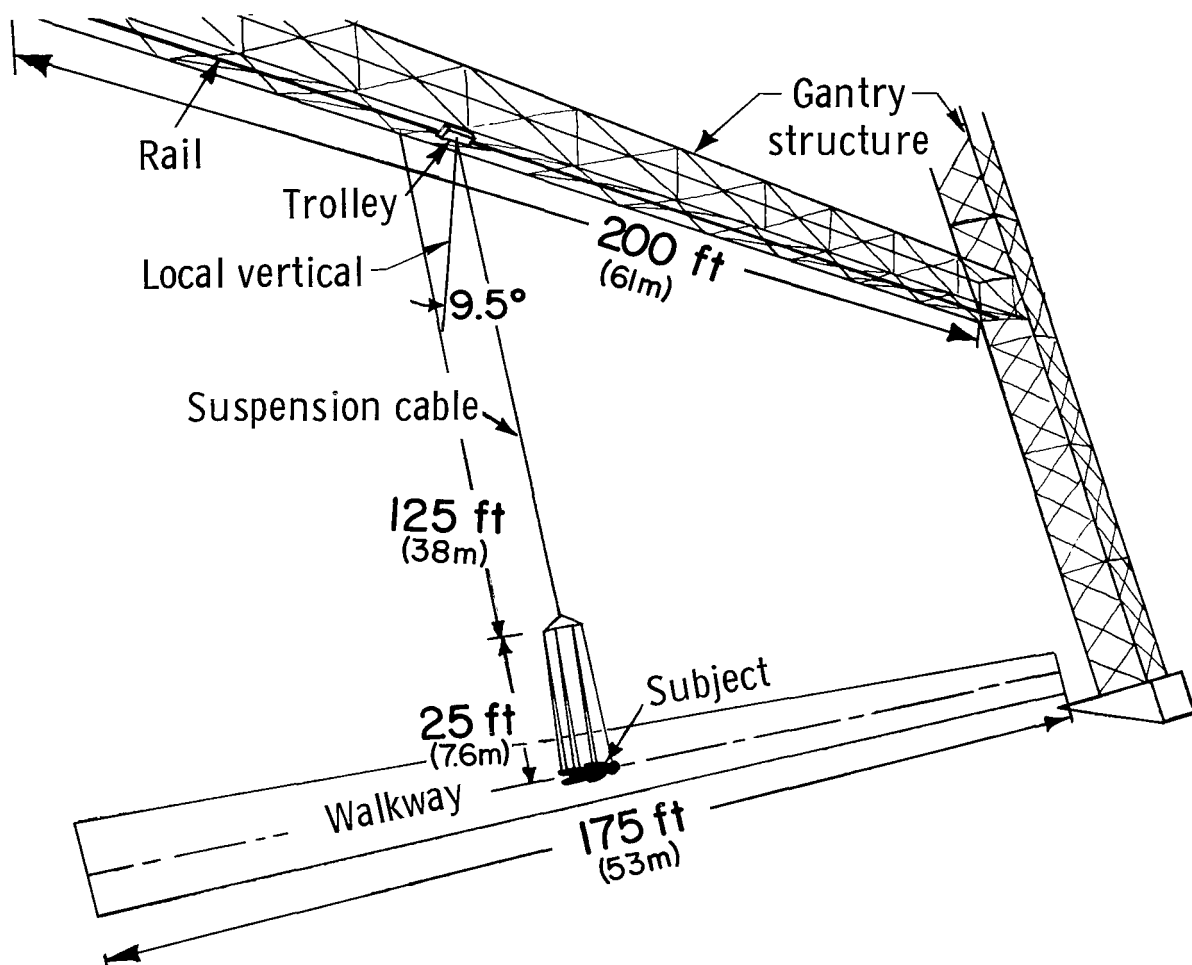


Figure 2.- Reduced-gravity walking simulator designed at the Langley Research Center with 150-ft (46-m) cable length.

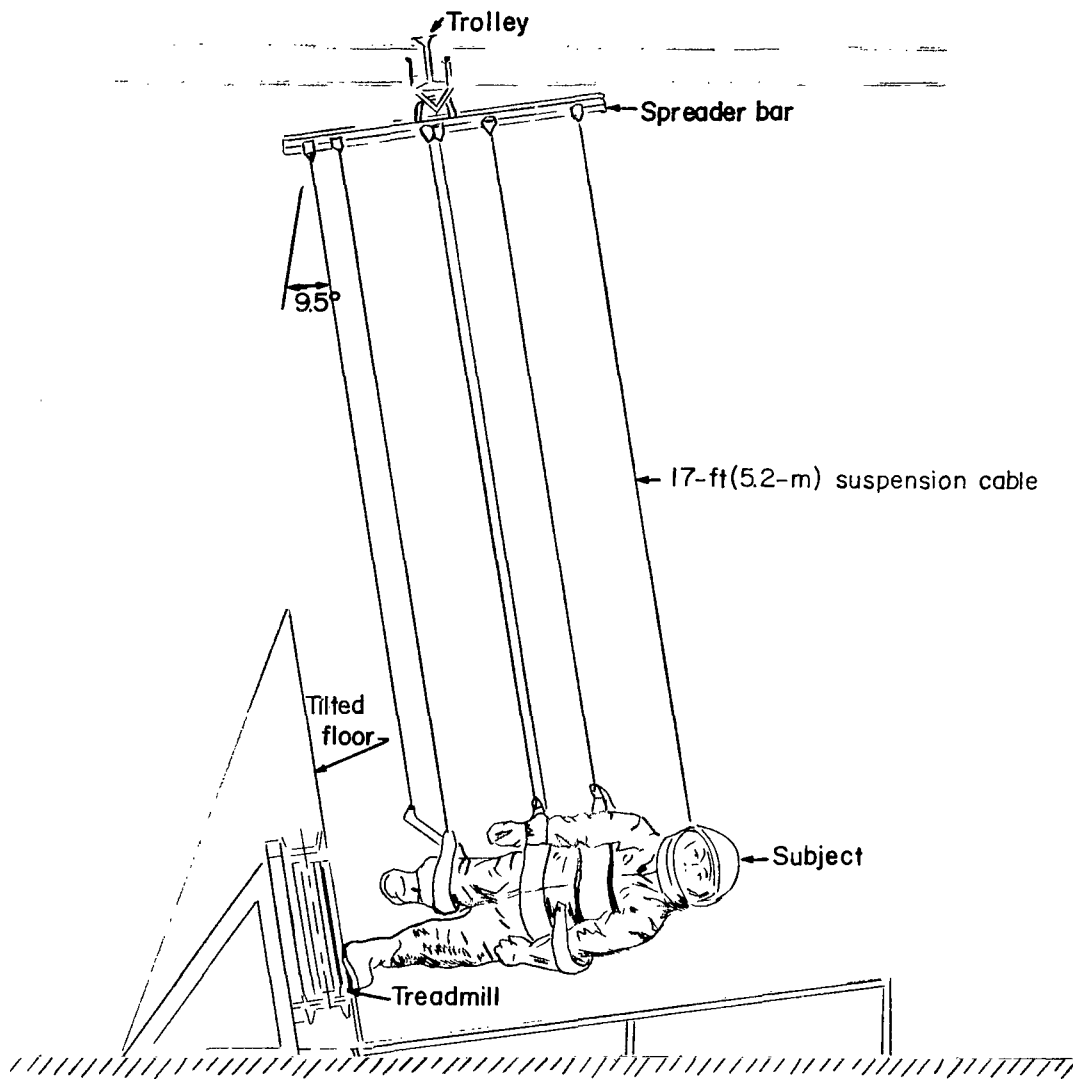


Figure 3.- Inclined-plane lunar-gravity simulator with 17-ft (5.2-m) cable length.

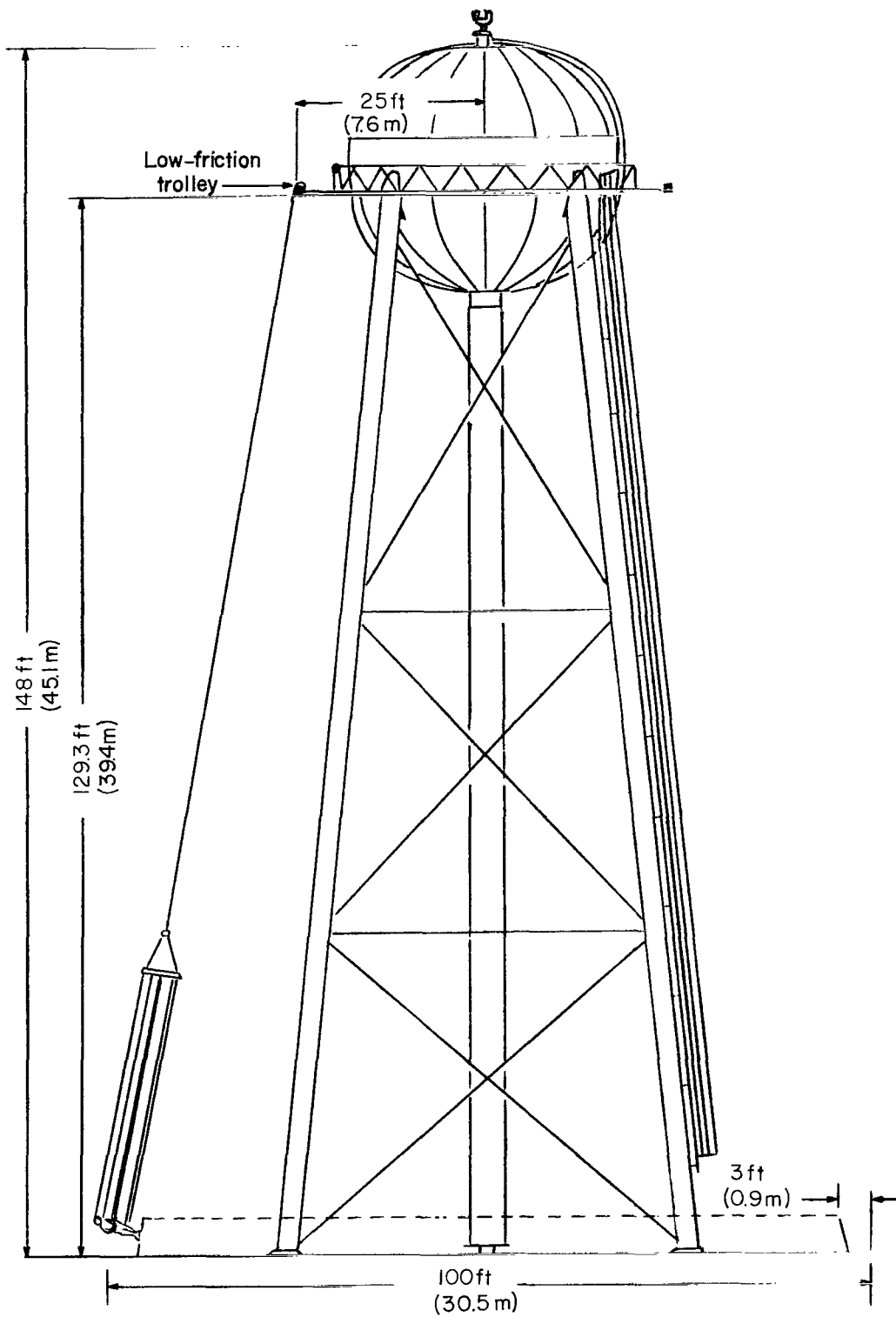


Figure 4.- Inclined-plane lunar-gravity simulator with 94-ft-diameter (28.6-m) circular walkway.

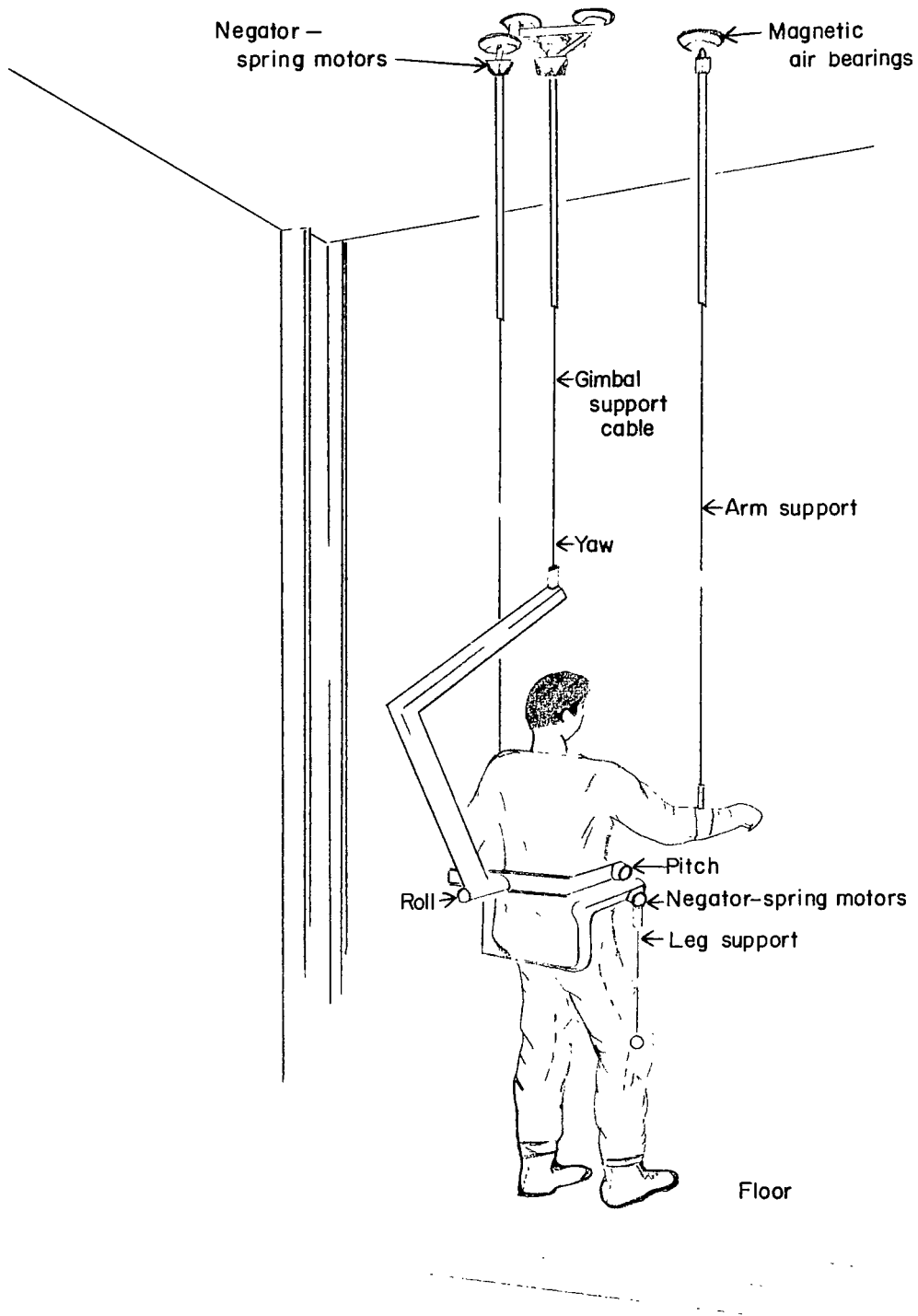


Figure 5.- Reduced-gravity simulator using negator springs.

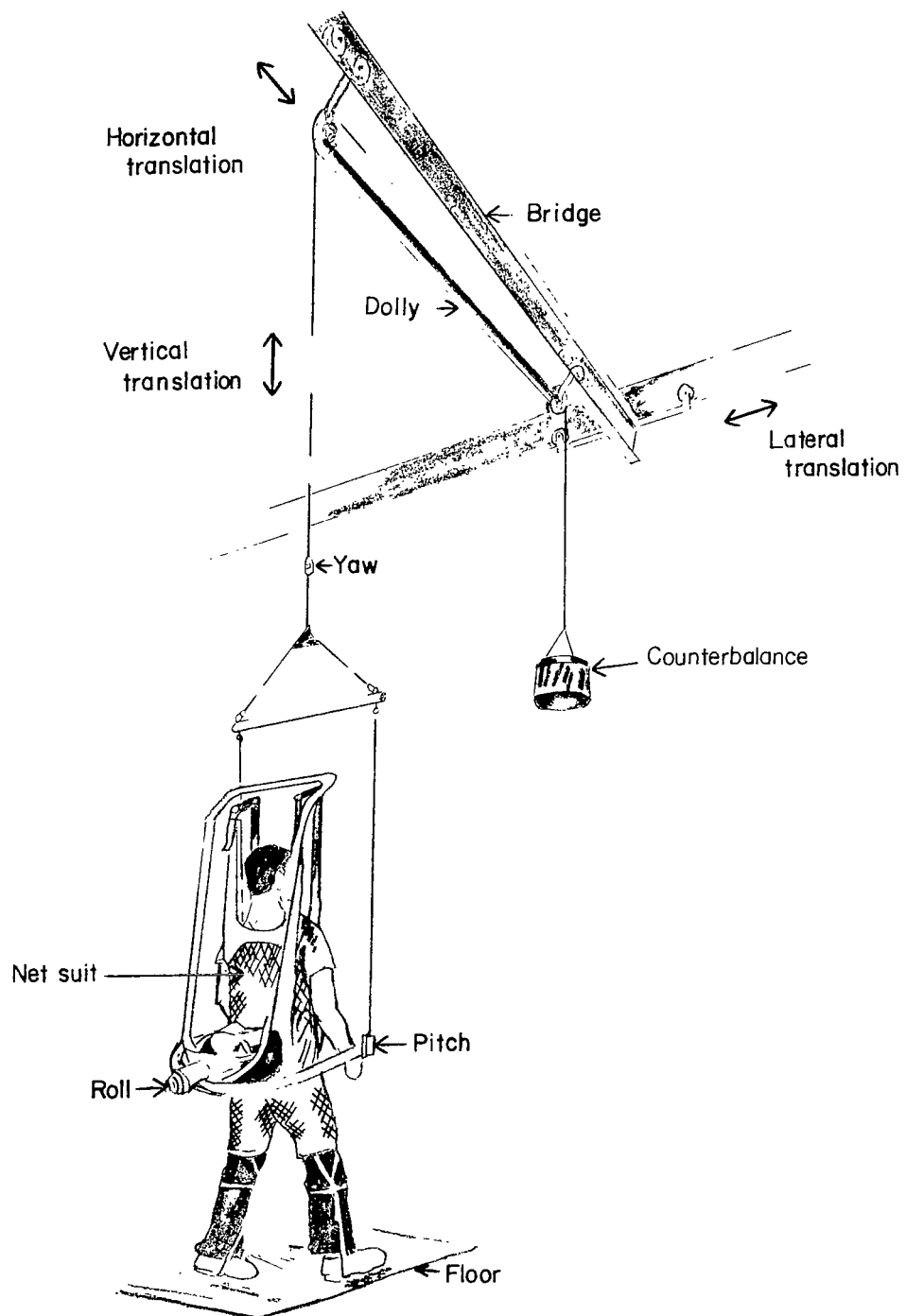


Figure 6.- Reduced-gravity simulator using a counterbalance and net-suit support.

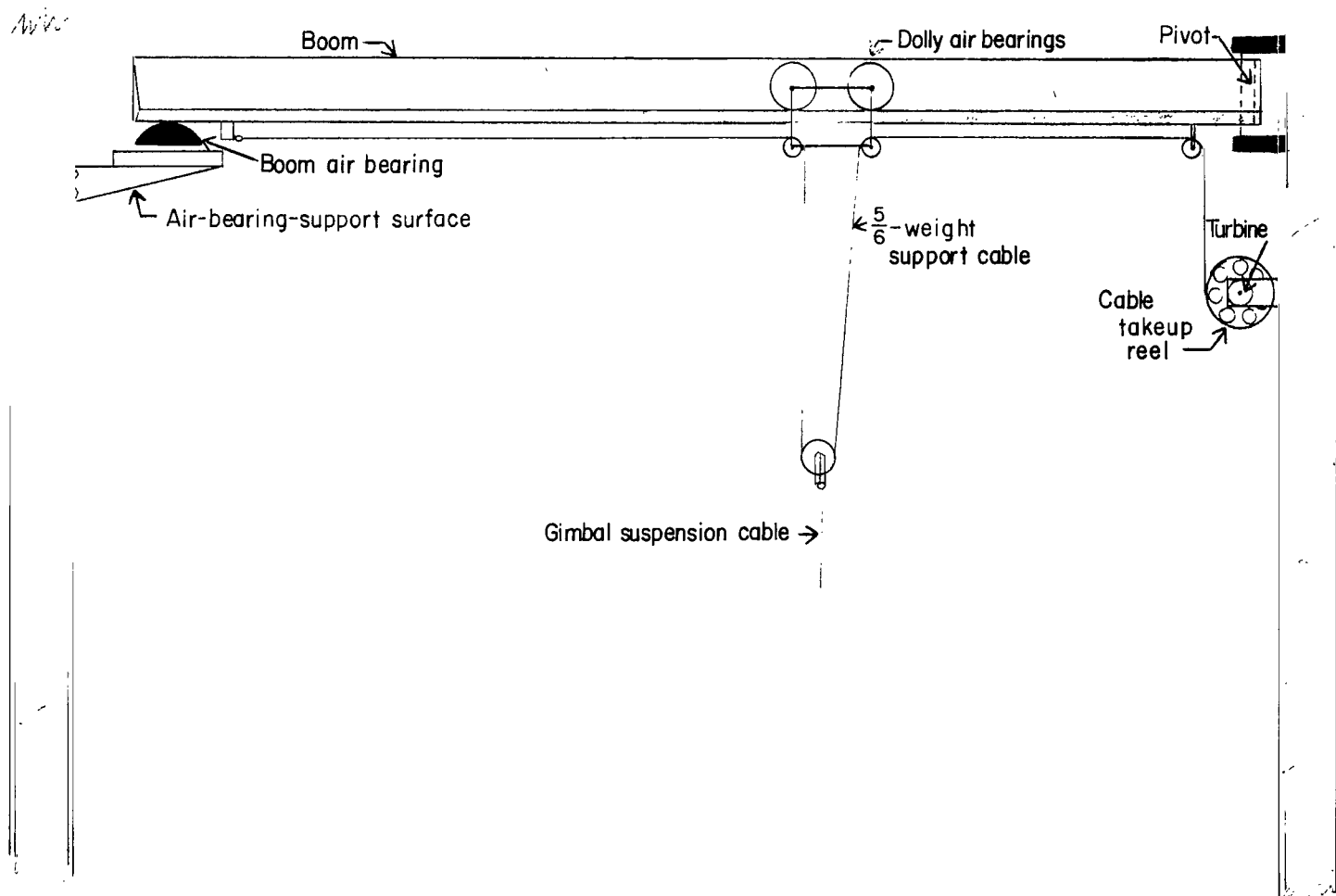


Figure 7.- Lunar-gravity simulator using stalled turbine and air bearings.

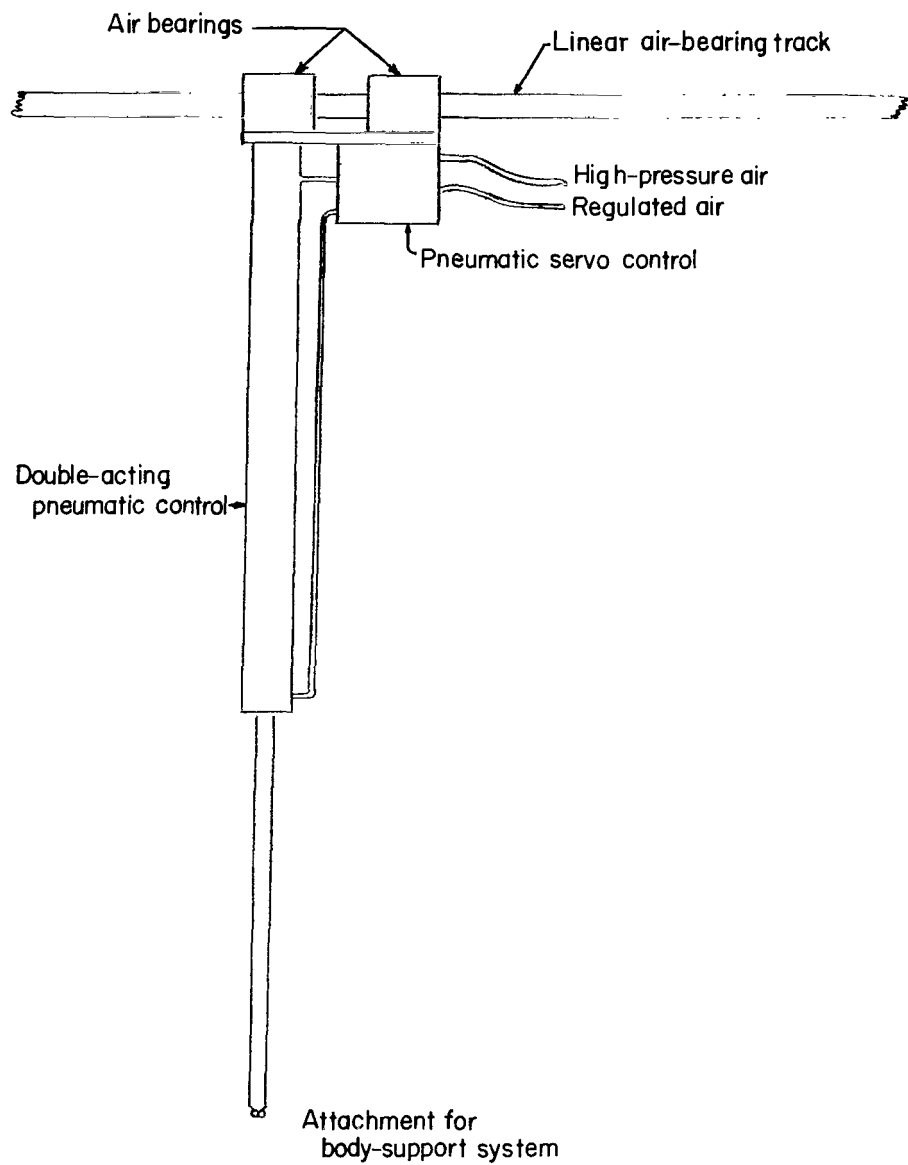


Figure 8.- Pneumatic-cylinder system used to provide simulated reduced gravity.

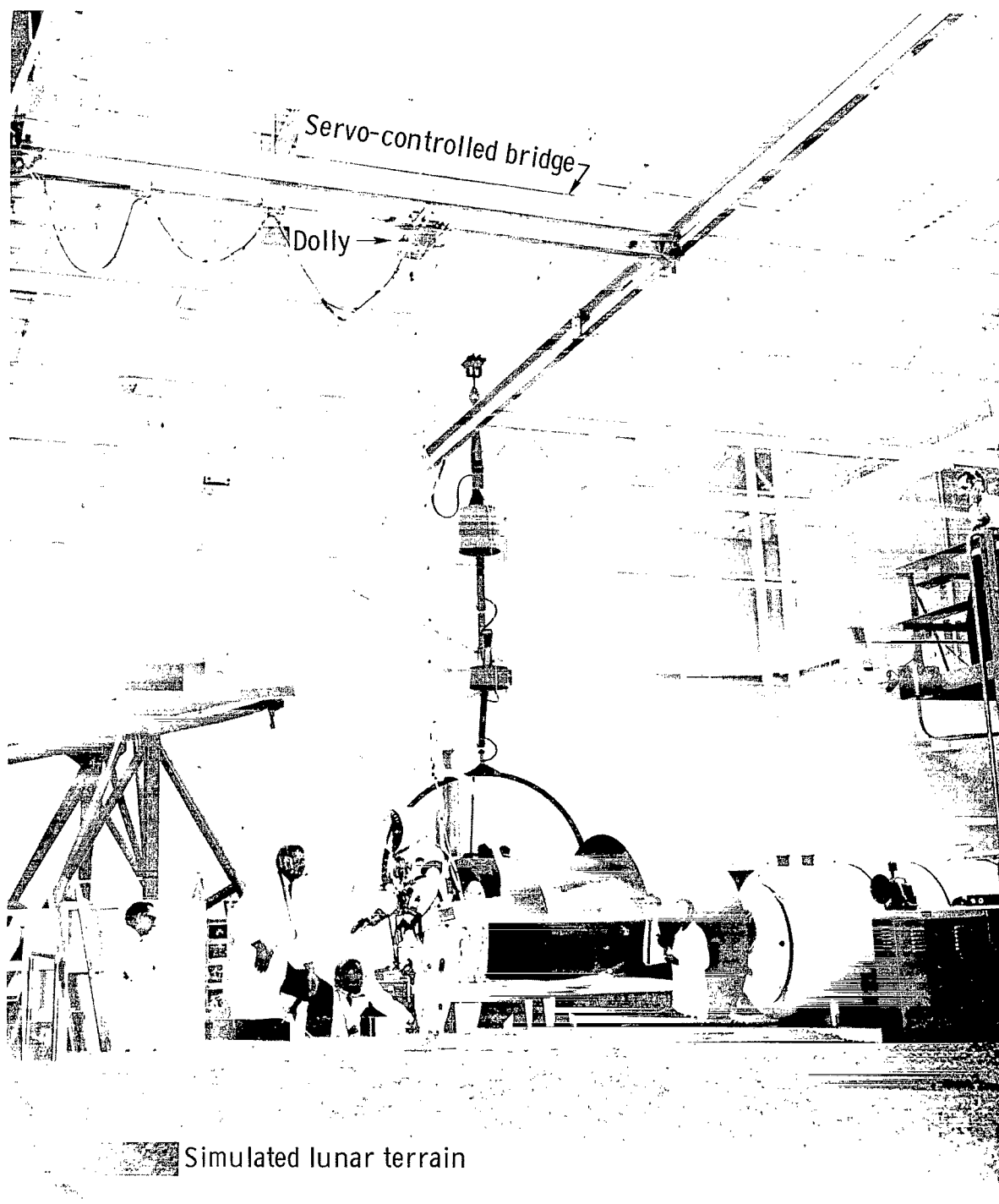


Figure 9.- Reduced-gravity simulator using servo-controlled bridge system with subject in the gimbal. L-70-1564

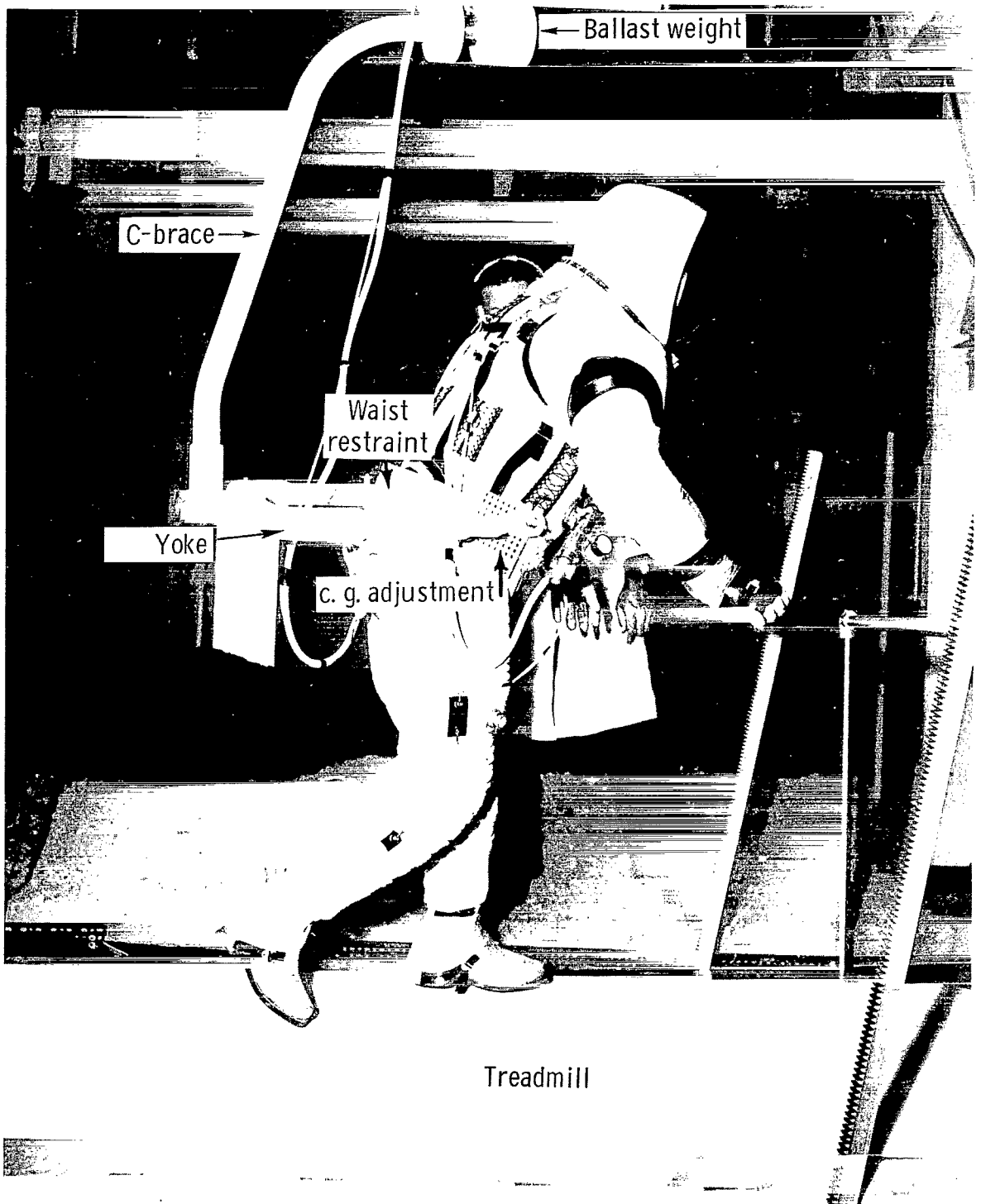


Figure 10.- Support system using waist restraint.

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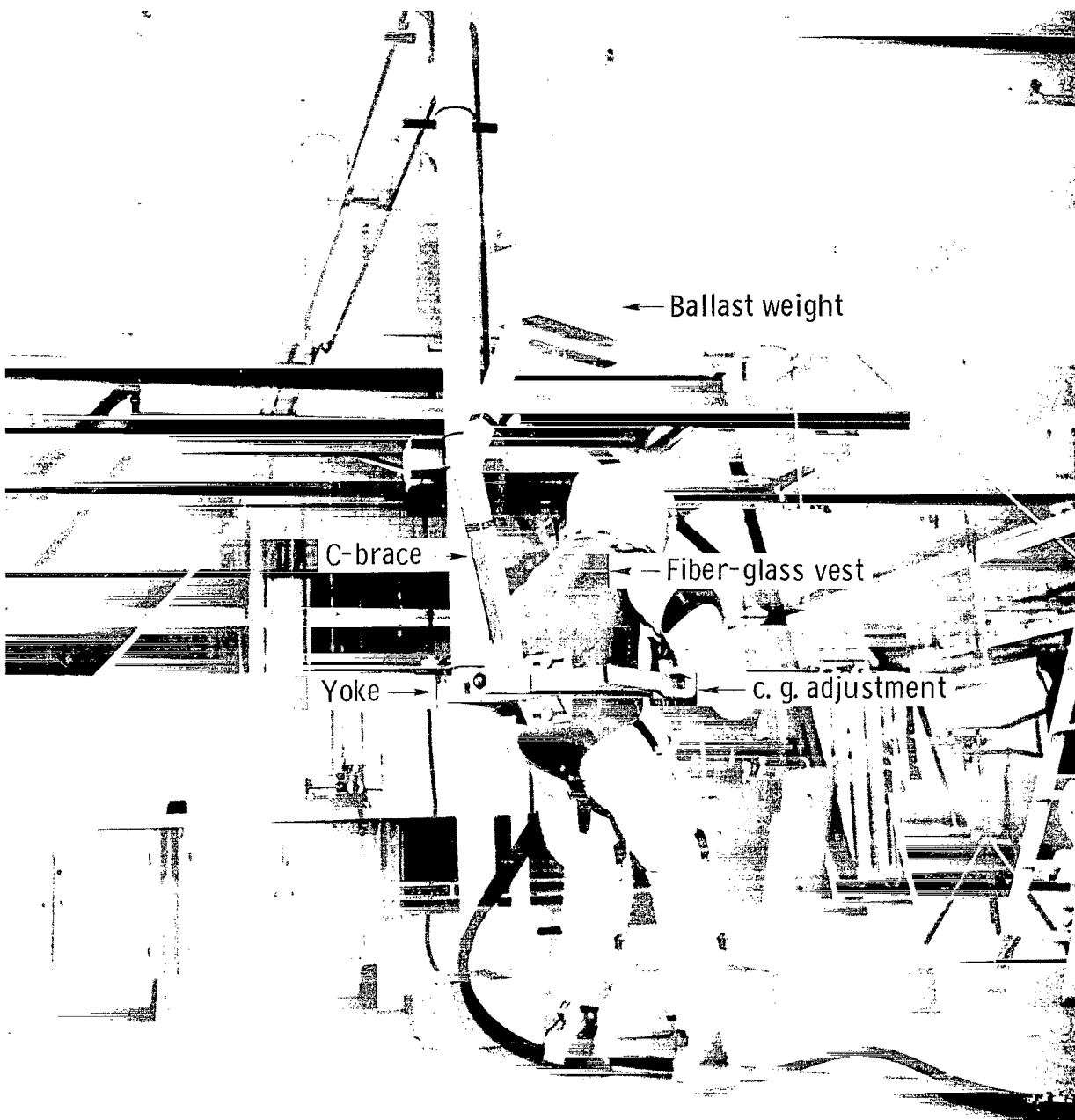


Figure 11.- Support system using fiber-glass vest.

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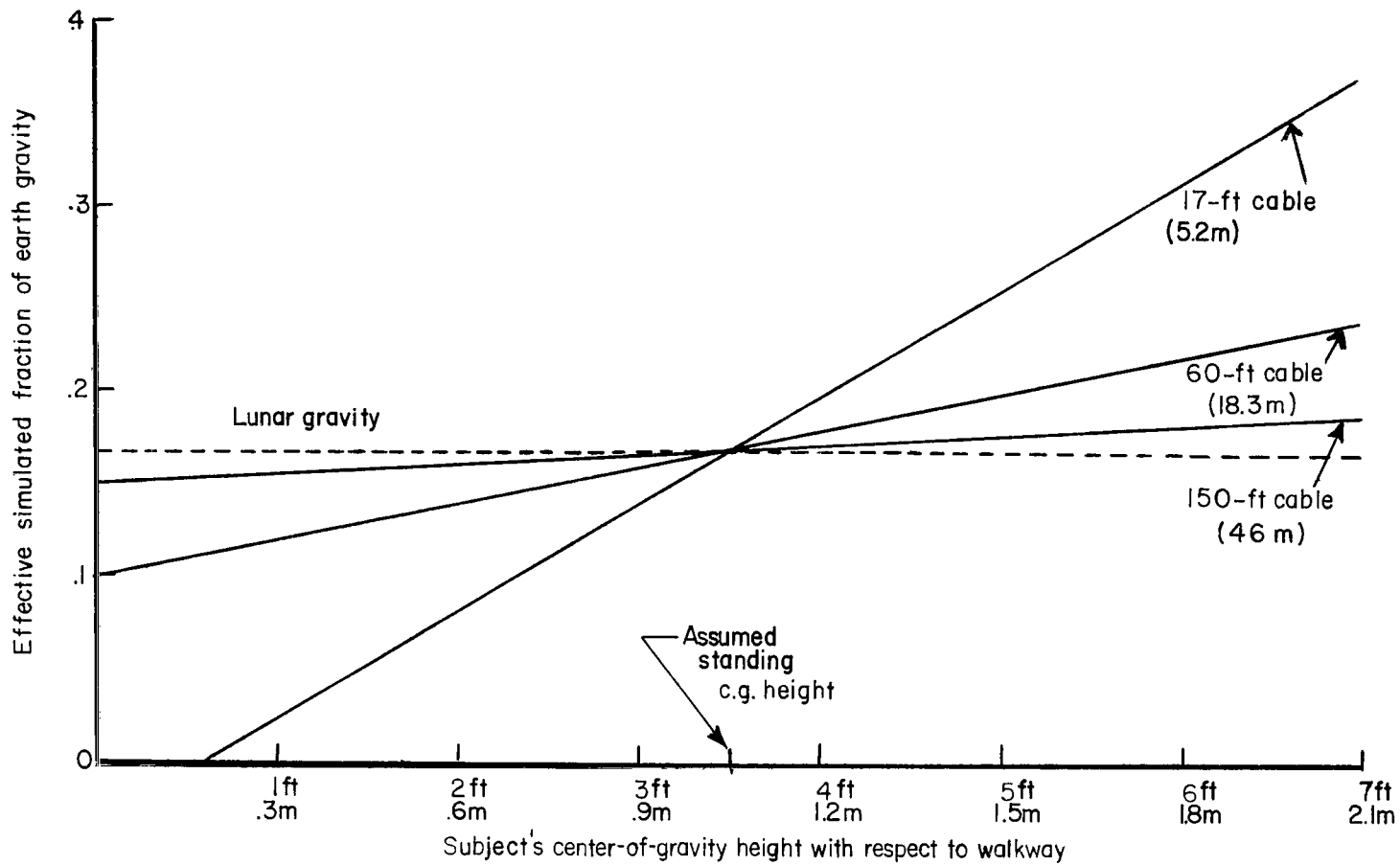


Figure 12.- Gravity level for inclined-plane simulator as a function of the subject's center-of-gravity height with respect to the walkway.

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